The Virtual Periscope

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LONG TERM GOALS

To see surface ships or obstacles, a submarine must rise close to the surface and expose a periscope. This sacrifices the submarine's inherent stealth, limits its submerged speed, and raises the risk of collision. The long-term goal of the Virtual Periscope investigation is to develop the technology that enables submarines to detect surface ships and obstacles from tactically useful depths and ranges.

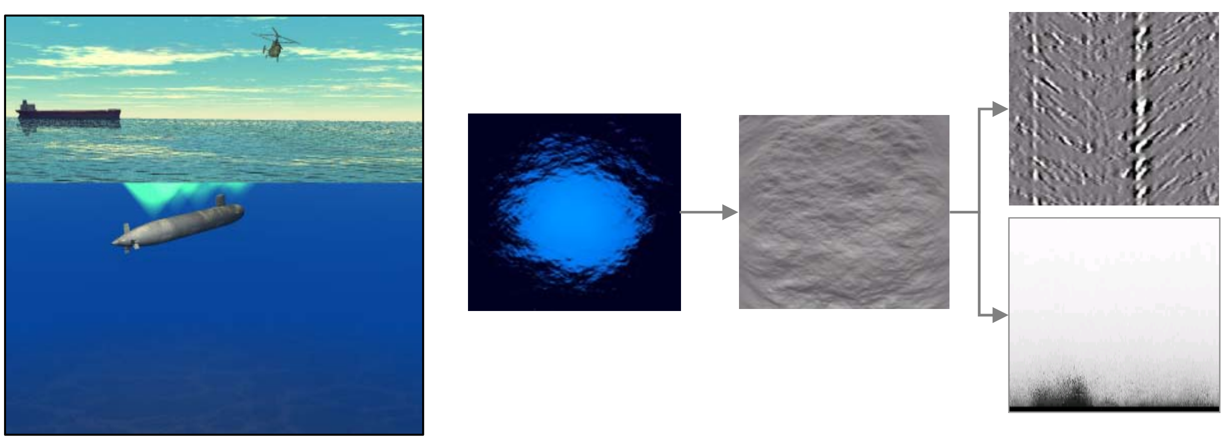

Figure 1: Virtual Periscope concept of operations (left) and signal processing overview (right).

OBJECTIVES

The scientific objectives of this investigation were far-reaching and included (a) Advance the through-surface viewing algorithm to demonstrate detection in simulated data of targets subtending between 2 and 3 degrees in elevation; (b) Make the algorithm ready for at-sea demonstration in the form of post-processing underwater imagery and meta data, performing the necessary motion compensation, wave estimation, and likelihood detection for useful through-surface performance; (c) Design, build, and pool-test the data acquisition system to be used on a seagoing platform; (d) Install the data acquisition system on a submarine, conduct data collection at sea, and perform post-processing to demonstrate useful through-surface imaging.

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APPROACH

The Virtual Periscope TEMPALT installation consists of a single upward-looking optical sensor mounted atop the sail, a portable control and data acquisition system used in the Control Room during data collection, a hybrid fiber-optic electrical hull penetrator (installed in place of the AN/BLD-1 electrical hull fitting), and interconnecting cables. An overall diagram is provided in Figure 2.

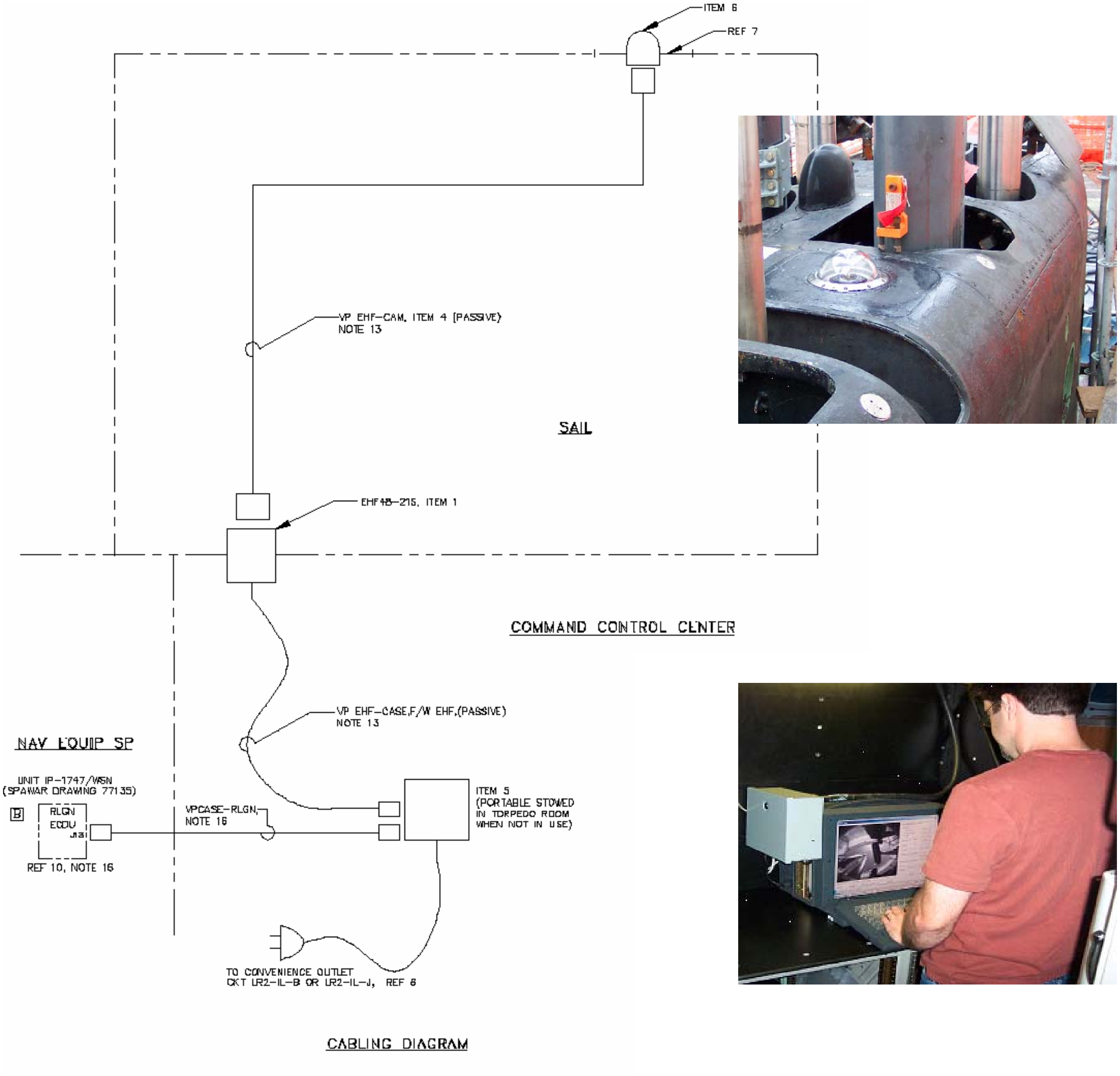


Figure 2: Virtual Periscope data collection system as installed on USS CHICAGO (SSN-721)

The sensor housing is mounted in the lookout station atop the sail. The station's existing hatch cover is restrained in the open position, with the sensor foundation providing a hydrodynamic fairing for the sail. The acrylic dome port's hemispherical shape protrudes three inches above the sail surface. When not in use the dome can be covered and protected from scratches by bolting on the stainless steel cover. The purpose of the dome port is to remove the magnification that occurs at the air-water interface of a flat port, and allow the camera to capture the full 140-degree field of view needed to capture all the refracted light penetrating the ocean surface and reaching the sensor.

Within the sensor housing is a Dalsa 1M30 CCD camera, fisheye lens, and interface electronics that collect underwater images and transmit them to the data acquisition computer in the Control Room for storage and post-processing. The FPGA circuitry inside the housing performs framegrabbing, fiber optic conversion, and remote control functions. The lens has a remotely controlled aperture to allow for collection in variable lighting conditions. The underwater cable connected to the housing provides 24 VDC power via copper conductors, and fiber optic transmission for data output and control functions.

The Portable Data Acquisition Computer (PDAC) is a self-contained workstation with integrated keyboard and monitor. With it the operator performs the data acquisition and control functions needed for post-processing and demonstration of through-surface viewing. The PDAC is connected to the electrical hull fitting via stowable umbilical, and to the RLGN via stowable Ethernet connection. Located atop the RLGN CDU chassis, the unused J13 connection streams binary navigation data needed for image motion compensation to the PDAC. The PDAC stores image and navigation data to removable hard drives housed in the PDAC chassis. Each hard drive holds about two hours of data, sufficient for multiple data collection runs before shutting down the computer and swapping disks.

The algorithm approach to the Virtual Periscope is as outlined in Figure 3. The data acquisition system collects underwater images of the entire Snell cone of light that penetrates the ocean surface. At a rate

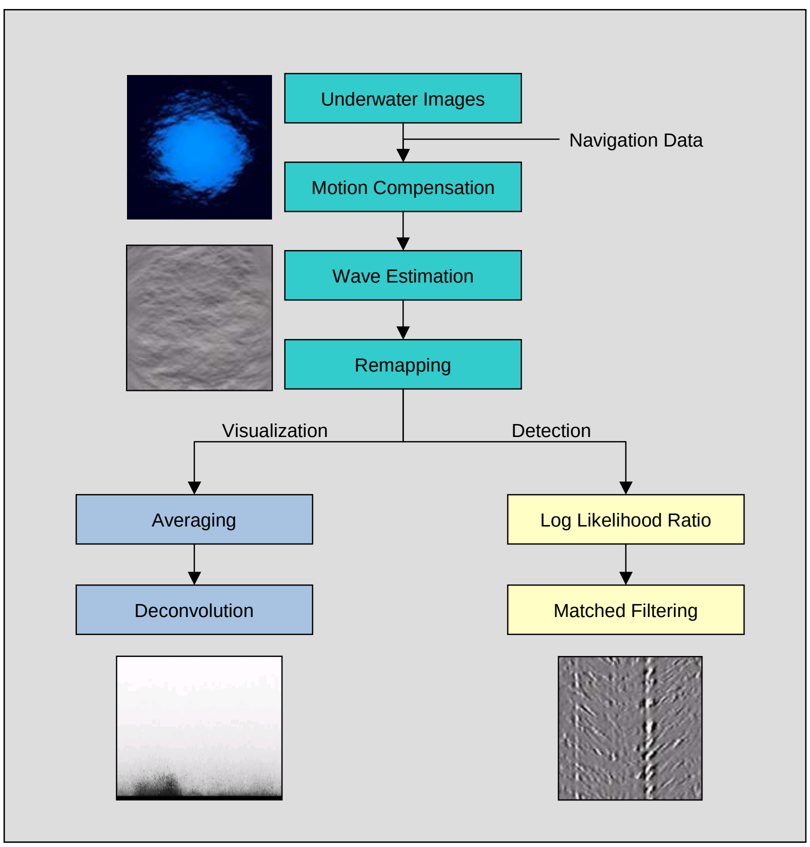


Figure 3. The algorithmic approach to through-surface visualization and detection.

of 10 frames per second, the camera sends digital images to the onboard computer for registration to an earth reference using the navigation information provided by the ship's inertial navigation system. The radial component of the ocean slope field is measured in each of the registered images by determining the position of extinction boundaries between groups of transmitting and internally reflecting pixels. The sparse set of radial slope measurements is then filtered in space and time to provide both radial and transverse slope estimates over the entire measurement region through the process of wave estimation. With the slope estimates thus obtained, the images are processed through either or both of visualization and detection streams. For visualization, the images are raytraced using the slope estimates to reduce the distortions due to the resolvable (wavelength longer than a pixel) surface waves and subsequently deconvolved to reduce the blur due to the unresolved (subpixel) surface waves. For detection, the images and the estimated slope fields are input to a statistical calculation that computes the likelihood that a ship silhouette is occluding light. The output of the detector can be presented in the form of a waterfall display that presents the likelihood as a function of time and bearing.

WORK COMPLETED

Upon completing the underwater data collection system, the team conducted an initial pool test to check system watertight integrity, conduct submerged testing of the data acquisition system in various lighting and sky conditions, and check system focus in the underwater environment. As shown in figure 4, the pool test vividly demonstrates that in still water, the through-surface view can be readily remapped to Cartesian coordinates and the entire above-surface reproduced with excellent clarity. Once the water surface is ruffled (in this case with a leaf blower), fidelity of the above-surface view is rapidly degraded. All objectives of the pool test were fully met, and the team was able to submarine installation and ocean testing.

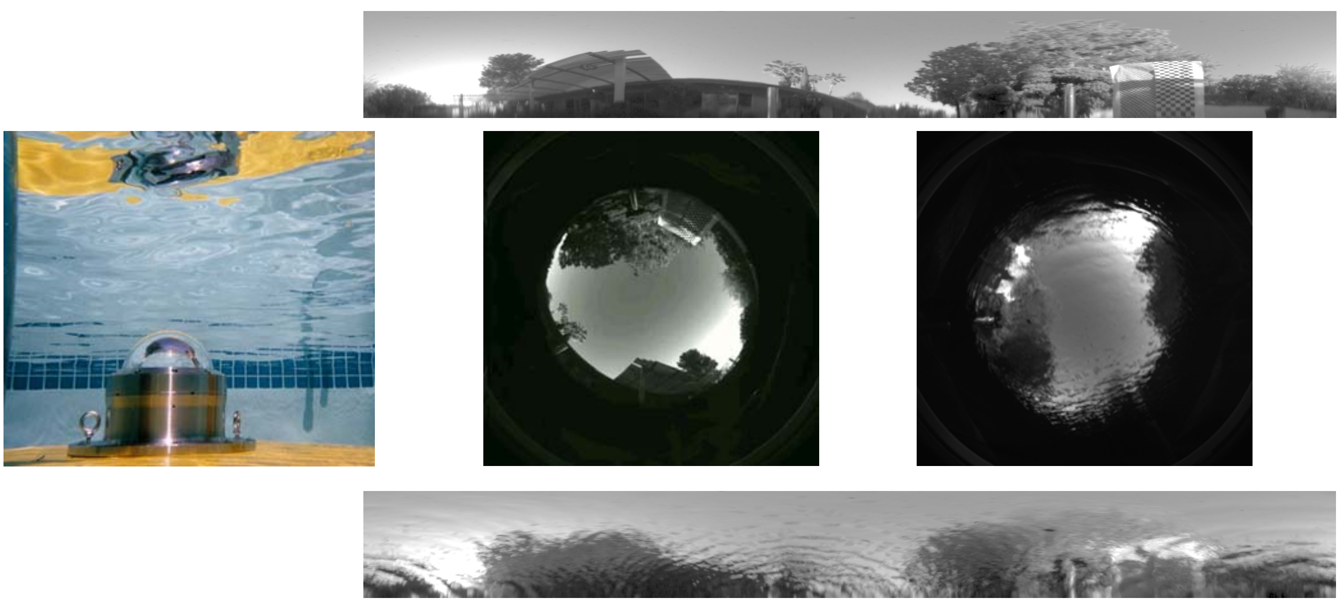
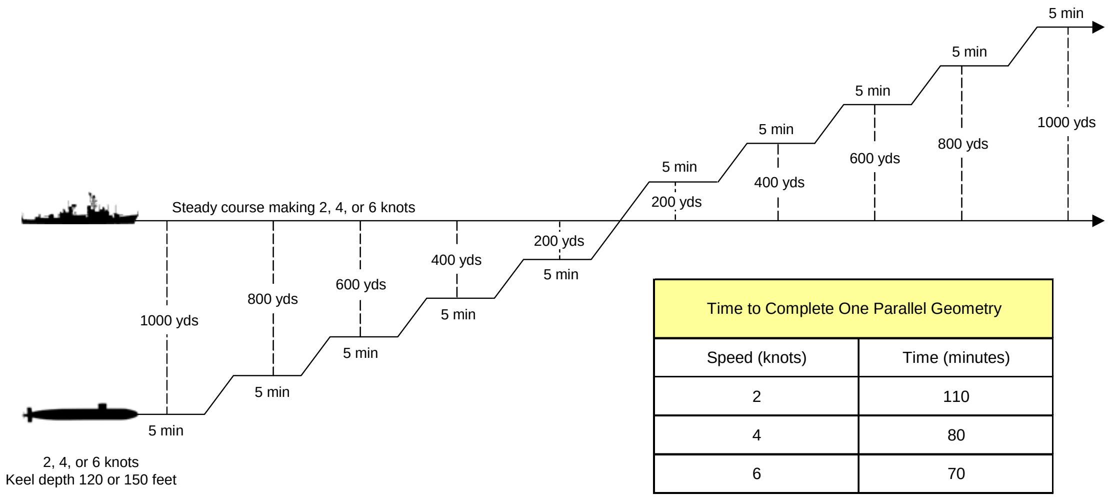


Figure 4. Initial pool test of the Virtual Periscope data collection system, showing the sensor setup (left), the remapped and undisturbed surface view (top and center), and the remapped and wind-blown surface view (right and bottom).

The full complement of Virtual Periscope testing consisted of a seven day transit from San Diego to Pearl Harbor, followed by a single day of testing in the waters south of Oahu with a dedicated surface target. The test schedule was comprised of several runs of one of four prescribed geometries: parallel, circular, racetrack (250-yard CPA), and racetrack (500-yard CPA). The surface vessel providing target services was USS LASSEN (DDG-82). LASSEN was generally tasked to be dead-in-the-water (DIW) or (in the case of the parallel geometries) to maintain a steady course and speed. USS CHICAGO ran the assigned geometry, observing the target with the submerged sensor while recording imagery and navigation data with the TEMPALT acquisition system.

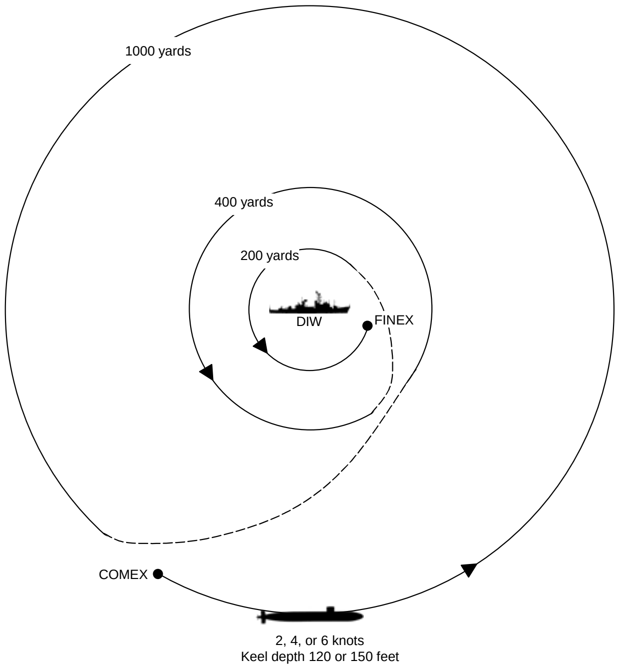
The Parallel Geometry shown in Figure 5 required the surface vessel to maintain a steady course and speed of 2, 4, or 6 knots. The submarine, operating at a keel depth of 120 or 150 feet, operated abeam on the same course and speed for several five-minute collection periods at various ranges. The submarine used a combination of active and passive sonar for station keeping.



Time to Complete One Parallel Geometry	
Speed (knots)	Time (minutes)
2	110
4	80
6	70

Figure 5: The Parallel Geometry for Virtual Periscope ocean testing.

The Circular Geometry shown in Figure 6 required that the surface vessel remain dead in the water (DIW). The submarine, operating at a keel depth of 120 or 150 feet, circled the target three times. Depth separation between the submarine and surface ship is maintained throughout.



Time to Complete One Circular Geometry	
Submarine Speed (knots)	Time (minutes)
2	151
4	75
6	50

Figure 6: The Circular Geometry for Virtual Periscope ocean testing.

The team collected eight hard disks (about one terabyte) of excellent image, navigation, and fire control data. CHICAGO and LASSEN supported the test fully, and we completed the planned parallel, racetrack, and circular geometries at ranges from 0 to 4000 yards. Several runs brought CHICAGO to pass directly beneath with spectacular results. The night data was done under a 96% moon and clear skies at 150 feet, PD, and broaching. Wave contrast was very good by day, and through-surface moon visibility leads us to believe that our algorithm will successfully detect navigation lights at night.

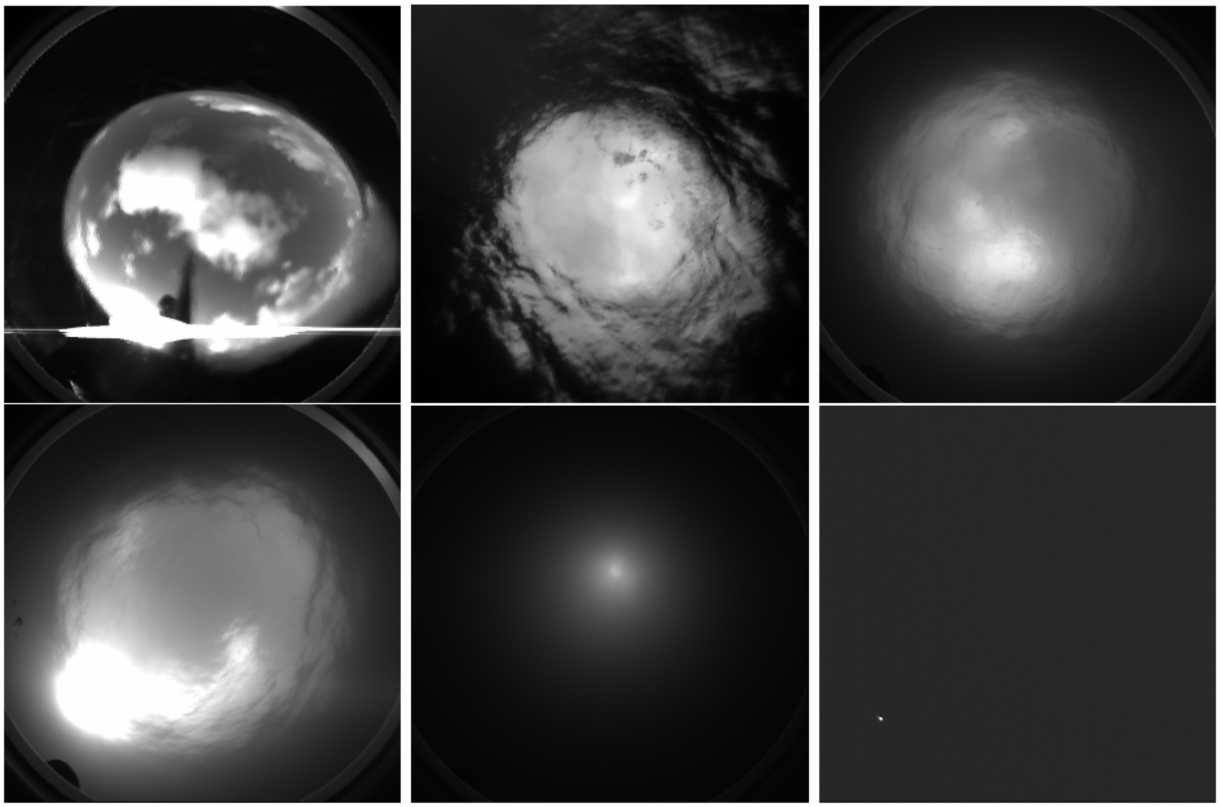


Figure 7: Summary of data collected in at-sea operations of the Virtual Periscope. Clockwise from upper left is broaching data; imagery from sensor depth of 10 feet; imagery from sensor depth of 100 feet; data collected at night; daytime data collected from 600 feet sensor depth; and data collected from 100 feet sensor depth with target hull coming into view.

In Figure 7 above, the breadth and extent of data collected at sea for post processing analysis can be seen. Perhaps most surprisingly, the sun can still be clearly seen from a sensor depth of 600 feet. While not much can be seen of individual wave facets, the sun's rays do in fact penetrate to great depths and future investigations may find ways to exploit this information. Also of immediate interest is the much different distortion effects taking place when the sensor is just beneath the surface at broaching depth. This may lead to unique algorithms that take advantage of the large tilting wave face and imaging above the region of first caustic focus. Contrasting the 10 foot versus the 100 foot deep imagery provides great insight into the scattering effects in the water column that must be accounted for in the wave estimation and detection processes.

RESULTS

The data selected for our initial demonstration takes place near sunset, with CHICAGO up-sun and slowly closing LASSEN until passing directly underneath. This choice was driven by the facts that these images had a manageable level of scattering of solar illumination (and hence good wave visibility) and that they were in the vicinity of a LASSEN passover, enabling an accurate reconstruction of the relative position of the ship without access to fire control data.

Except for a small set of analyses using San Clemente Island data collected in 2001, the Virtual Periscope algorithms had been developed using simulated data. Transitioning the algorithms for application to sea test data presented several challenges. First, the imagery had to be temporally synchronized with navigation data supplied by the RLGN system so that the imagery could be properly registered to an absolute spatial and angular coordinate system. Using the RLGN navigation data for platform motion compensation, we had to apply corrections for lag and drift between the imagery and the navigation. This was accomplished with data from a synchronization maneuver in which CHICAGO executed a 10 degree downward pitch followed by a 10 degree upward pitch. By tracking the position of the sun during this maneuver and correlating against the RLGN data, we were able to determine the time lag to within a few tenths of a second. Taking this lag into account, the sun position remained fixed in the registered imagery as expected.

A second challenge in the sea test data was to cope with the highly nonuniform illumination of the scene. Previously, the algorithms had been designed for the situation of a completely uniform sky, as might be encountered on an overcast day. A uniform sky simplifies the situation considerably in a number of respects, permitting an analytic formulation of the gradiometer as one example. With the sun on the horizon and clouds in the sky, the selected dataset did not at all resemble uniform illumination. In response to this challenge, we developed a new approach to gradiometry (the first-pass determination of wave slope from measured brightness) that was demonstrated to be much more robust against highly variable illumination associated with sun and clouds. Testing this approach against simulations with non-uniform skies, we found much better performance than our earlier gradiometry technique (designed for uniform skies), without significant performance loss when the sky is actually uniform. The technique hinges on collecting brightness statistics locally within an image and intelligently interpolating between distributions measured in different locations. We applied the new gradiometer to the LASSEN data and generated plausible slope measurements across the entire Snell cone. A similar technique was also built into our likelihood ratio detector to improve performance against nonuniform skies.

A third challenge was to compensate for the motion of the platform in the wave estimator. Earlier work with simulations and with the San Clemente Island dataset had been based upon a stationary sensor at a fixed depth. We developed algorithms for motion compensation that were demonstrated in simulations with a moving sensor to achieve wave estimation accuracies comparable to a stationary camera (second order effects come into play with a moving sensor that depend on the relative speed and direction of the camera with respect to the wave field). Using the RLGN data to register the imagery and applying the motion compensation algorithms, we produced plausible wave estimates over a span of data in which the platform is performing a tight circular orbit.

A fourth challenge was presented by nonlinear wave propagation. This is a complex interaction among waves that is not straightforward to include within the wave estimator. We have been concerned about the adverse impact of nonlinear waves on estimator performance, anticipating that it would be comparable to that of relief distortion. We updated our simulation with a new capability to model nonlinear surface effects using a simple approximation that accurately represents nonlinearities to first order. The most noticeable effect in this approximation is the advection of short waves by longer waves and the sharpening of wave crests. We found that, as anticipated, wave estimator performance was significantly worsened when this effect was included in the simulation. We addressed this problem by building compensation routines into our wave estimator and have found that performance can be partially recovered in comparison with simulations without wave advection. With further work, a complete recovery may be possible.

The likelihood detector also underwent significant revisions in the course of analyzing the sea test data. In a similar fashion as the gradiometer algorithm, the detector was also generalized to cope with highly nonuniform illumination. It was also generalized to detect larger targets (i.e. those with significant signal inside the Snell cone) so that it would behave well with the LASSEN at close range.

After converting the detector algorithm into a much faster C++ code, we processed target-absent and target-present data to provide the likelihood detection algorithm with the slope and brightness statistics that form the likelihood ratio. In our first end-to-end test, we applied the likelihood detector to the wave estimator output and gained a tentative though-surface detection on LASSEN well before the hull emerged in the raw imagery. The detector behaved well, detecting the LASSEN at a range of 130 yards in spite of the much larger signal produced by the sun on the horizon.

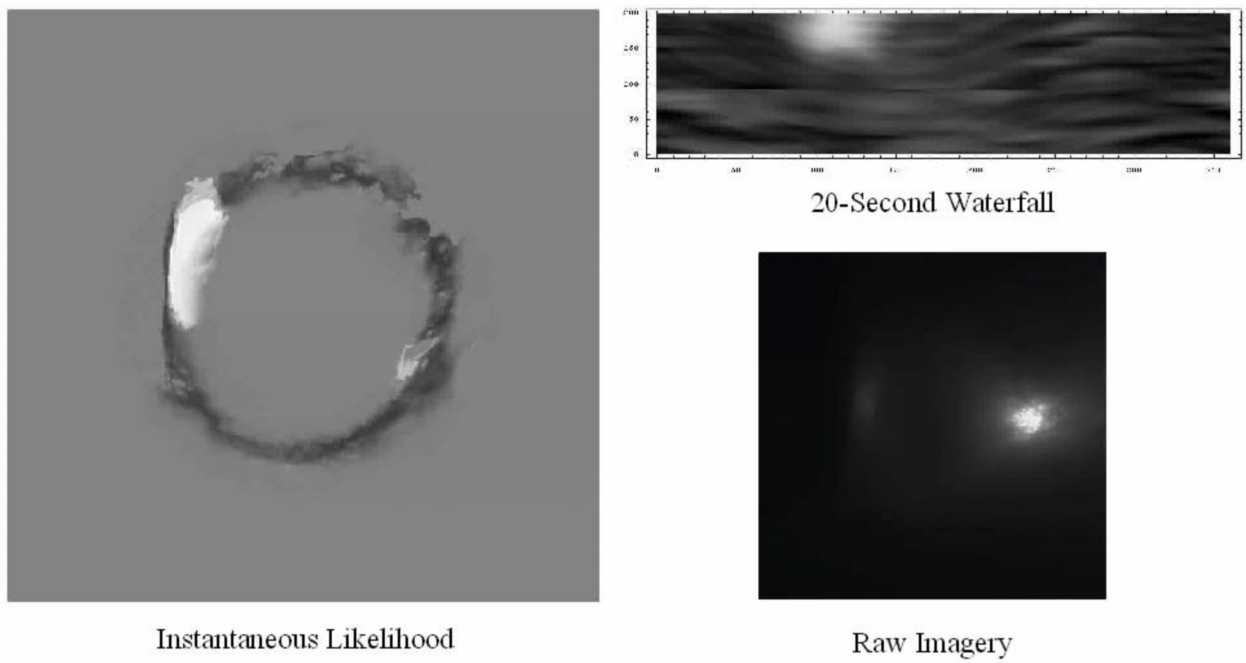


Figure 8. Initial results of applying the detection algorithm to the ocean target data in an end-to-end test. To the left is the instantaneous likelihood output, displayed as a single line in a 20-second waterfall display at top. In the raw imagery the sun is most visible, with the reflected glow of the superstructure coming into view.

A number of promising areas of investigation remain for us to extend the detection limit to a more tactically useful range. One of the most prominent is the effect of volume scattering, especially when sunbeams are present. While we have successfully compensated for sky illumination that is spatially nonuniform, we have observed that temporal fluctuations in the illumination as direct solar illumination is refracted by long wavelength surface waves produce strong responses in the gradiometer and likelihood detector that are unrelated to the presence of the target. Both sets of algorithms could be designed to cope with brightness fluctuations of those spatial and temporal scales, leading to higher quality wave estimates and more sensitive detector output.

TRANSITIONS

While this research has not yet transitioned to an acquisition or operational command, it is being conducted in concert with the submarine imaging acquisition office of NavSea, PMS 435. It is also being conducted with the mutual benefit of Low Observable Periscope research which is sponsored by ONR, DARPA, and NSWC Panama City.

RELATED PROJECTS

Work on the Virtual Periscope project is related to the developmental work on the Low Observable Periscope. While both are through-surface sensors, Virtual Periscope is designed for a sensor depth of 150 feet while Low Observable Periscope is intended for a depth of only a few inches. The Virtual Periscope effort is focused on creating an algorithm that can *detect* the presence of a surface ships at maximum range for collision avoidance. By operating on imagery data collected from only a few inches deep, the Low Observable Periscope algorithm aims to produce imagery of sufficient clarity to visualize the above-ocean scene for covert surveillance purposes.